Proceedings World Geothermal Congress 2023
Beijing, China, April 17 – 21, 2023

A new weighted model and quantification of the most favorable drilling targets of Berlín Geothermal Field using Leapfrog Geothermal

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Keywords: Brittle/ductile transition, conceptual model, fault system, favorable areas, formation temperature, geothermal system, geothermal exploration, heat flow, leapfrog geothermal, magnetotellurics (MT), resistivity, seismic monitoring, thermal gradient, weighted model.

ABSTRACT

The Geothermal Field of Berlín is in the southern flank of the Central Graben and the northwest sector of the Berlín-Tecapa volcanic complex in El Salvador. The volcanic activity of the region is related to the tectonic interaction in the subduction zone between the Cocos and Caribbean plates (DeMets, 2001). Geoscientific studies began in the 1960s, and after that, the field went to commercial operation on a small scale in 1992 with two back pressure units of 5 MW each (Montalvo and Axelsson, 2000). During the following years, different multidisciplinary studies were carried out to characterize the geothermal system that permitted the finding of new target areas. As a result, there is currently a total installed electrical capacity of 109.2 MWe (without the back pressure units). However, it is essential to continue studying other types of information to observe anomalies supported by different correlations and datasets that permit quantitatively identifying the most promising drilling targets of the area.

According to de above, a weighted model of the most favorable drilling areas for Berlín Geothermal Field has been developed. It is based on the last updated conceptual model (LaGeo, 2019), new interpretations, and new models created in the Leapfrog Geothermal program. Previous information has been interpreted and updated to a digital format to be integrated into a 3D model (Leapfrog, 2021). The various datasets provide the basis for the weighted model, which is primarily subdivided into four groups: 1. Surface data, 2. well data, 3) well logs, and 4) other data types like the 3D resistivity model. The 3D model results have been correlated and integrated into the weighted model, which purpose is to improve understanding of the nature and characteristics of the geothermal reservoir to minimize risks for future drilling targets.

The resulting workflow describes how to bring together multidisciplinary interpretation results, highlighting areas of uncertainty and the required future work. According to the most favorable areas of the weighted model, eight different drilling places or areas are suggested. The best parameters converge from all 3D models created previously, indicating favorability equal to or higher than 85%.

1. INTRODUCTION

The geothermal activity in Central America is due to the subduction zone, where the subduction of the Cocos Plate underneath the Caribbean Plate occurs at the Middle America Trench, pushing the rocks to great depths, while magma and heat are transferred towards the surface (DeMets, 2001). The subduction area is very seismically active due to rapid plate convergence, creating different volcanoes, and in many cases, high temperature geothermal areas with high potential energy, like Berlín Geothermal Field located in El Salvador.

1.1 Geological Setting

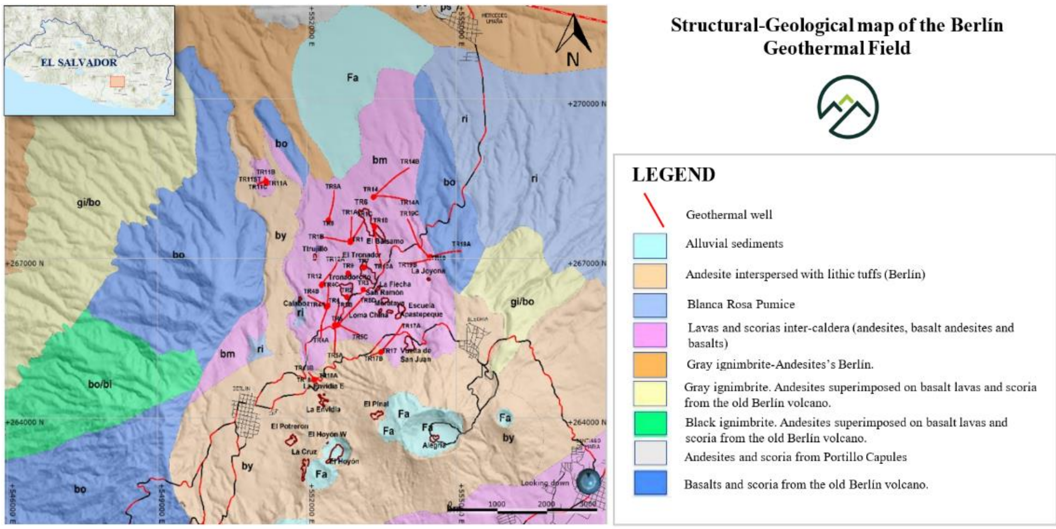

Figure 1: Geological map of Berlín geothermal field (modified from LaGeo, 2019). The inset map shows the location of geothermal area in El Salvador.

Berlín Geothermal Field is in the southern flack of the Central Graben and in the northwest sector of Berlín-Tecapa volcanic complex, which is a stratovolcano where lava flows, pyroclastites, and epiclastites alternate, mainly andesitic, and basaltic-andesite rocks (LaGeo, 2019). The area is composed of several volcanic cones surrounding the area, specifically to the SE of the old volcano of Berlín.

1.2 Geophysical overview

Different geophysical studies have been carried out by LaGeo. During 2012-2019, a new 3D resistivity model was created with 13 new MT soundings located in the center, northwest, and south of the field (LaGeo, 2019). Figure 2 shows a N-S lying resistivity cross-section based on 3D inversion of MT data, with three main different layers; a low-resistivity layer associated with altered clay minerals (smectite) and resistivity < 10 Ωm; a transition zone of the geothermal system, with resistivity between 10 and 30 Ωm; and the production reservoir with resistivity between 30 and 90 Ωm, extended to the south of the production.

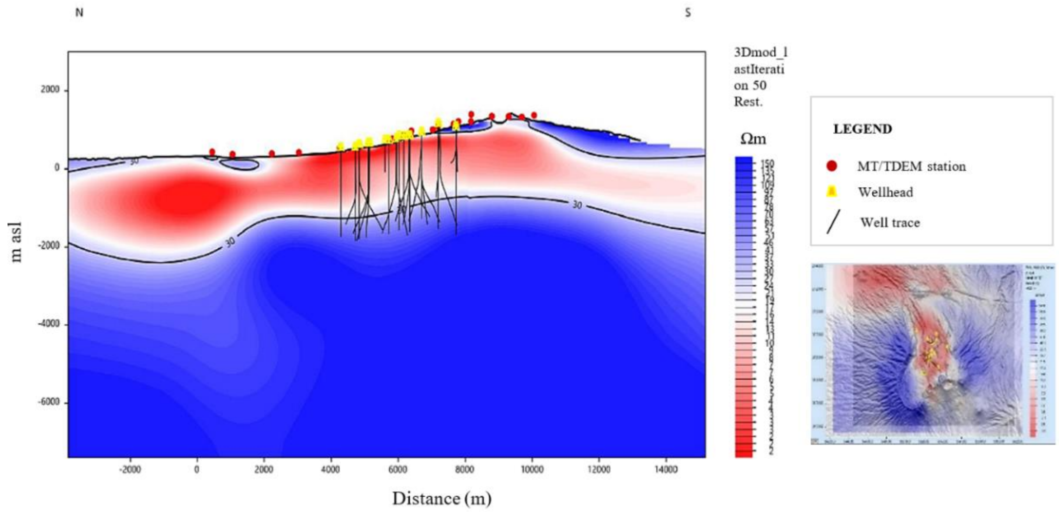

Figure 2: N-S lying resistivity cross-section based on 3D inversion of MT data. The cross-section shows the 30 Ωm contour that represents the top of the reservoir (black contour), the smectite cap above the reservoir with resistivity < 10 Ωm, the locations of the geothermal wells close to the profile (black tracers) and the MT/TDEM sounding (red circles) (LaGeo, 2019)

The seismicity in the area was recorded in 2013-2019. The results were compared with the resistivity model based on 1D inversion (see Figure 8). The possible presence of a body with ductile properties at approximately 6,000 m b.s.l was identified from the seismic studies, which is consistent with the deep conductive anomaly and assumed to be related to the heat source (LaGeo, 2019).

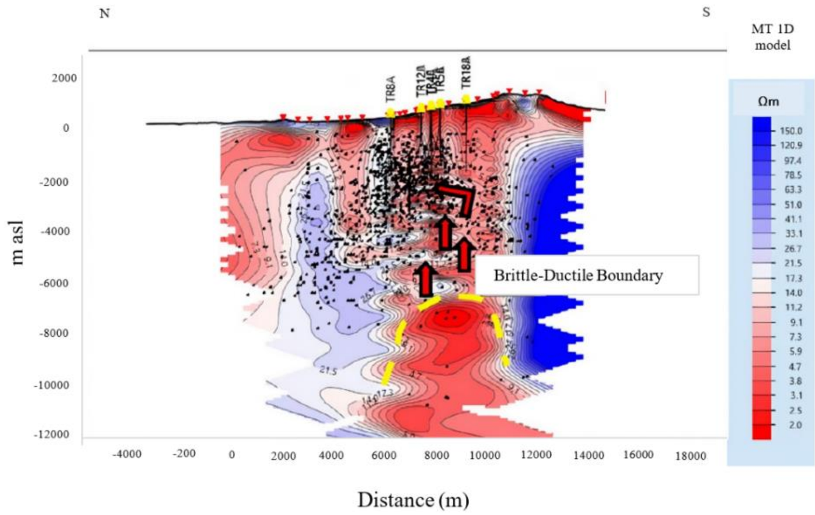

Figure 3: Comparison between the resistivity model based on 1D inversion and the earthquakes location, recorded in 2013-2019 – N-S profile. Red arrows indicate the upflow and the dotted yellow line the Brittle-Ductile interface (LaGeo, 2019)

1.3 Data from wells

1.3.1 Lithological data

The lithology is divided into four lithological units (I-IV). The principal types of rocks are andesite or andesite-basaltic lavas, pyroclastic rocks like tuff, and ignimbrites. Unit I is made up of superficial materials, e.g., andesite lavas alternating with some pyroclastic rocks. This Unit has high permeability corresponding to the superficial aquifer. The thickness of Unit I is between 400 and 990 m. Unit II is made up of pyroclastic rocks with secondary fissures, Unit III is related to tuff, and Unit IV is made up of andesitic lava and is related to the geothermal reservoir (LaGeo, 2019).

1.3.2 Alteration mineral facies data

The hydrothermal alteration in geothermal fields is different in different types of reservoir rocks (Kristmannsdóttir, 1985). The intensity or degree of alteration is related to several factors such as permeability (related to the gas content and hydrology of the system), rock composition, temperature, duration of the activity, temperature-pressure, hydrothermal fluid composition, and hydrology (Kristmannsdóttir, 1985; Browne, 1978; Reyes, 2000; Franzson, 2008).

In high-temperature geothermal fields in Iceland, the pyrite mineral is associated with permeable zones (Kristmannsdóttir, 1979), but in Berlín geothermal field, the pyrites+zeolites are associated with permeable zones at intermediate temperature (150-220°C) (LaGeo, 2019). However, between -900 and -1900 m a.s.l (thickness of the deep reservoir) pyrites+epidote minerals have been identified. The pyrite minerals correspond to permeable zones at high temperatures (230-260°C).

The analysis methods used to determine hydrothermal minerals of alteration are petrographic microscope and X-Ray diffraction analysis (LaGeo, 2019). In general terms, the hydrothermal alteration in Berlín is characterized by secondary minerals, like:

- Cristobalite, quartz and zeolites.
- Clays and chlorites.
- Epidote.
- Calcite.
- Oxides and hydroxides.
- Sulfides.

The hydrothermally altered rocks are grouped into six principal facies, argillic, argillic-phyllic, phyllic, phyllic-propylitic, propylitic, and potassic. Generally, each type of alteration represents a stabilized temperature according to the different types of identified minerals (LaGeo, 2019).

The argillic facie clay minerals, such as smectite and zeolites, are altered at low temperatures (stabilized temperature between 50 and 150°C). The argillic-phyllic facie clay minerals, like quartz, calcite, and zeolite, are altered at a stabilized temperature of 150-180°C. The phyllic facie, the same minerals as the previous facie re altered at higher stabilized temperature (200-230°C). The formation of epidote minerals happens in the phyllic-propylitic facie as well as, the chloride. The stabilized temperature in this facie is 230-260°C. The propylitic facie is characterized by high content of epidote deposited in fissures; also, it is associated with minerals like quartz, calcite, and other minerals at high temperatures. Stabilized temperatures are estimated between 260 and 300°C (LaGeo, 2019).

1.3.2 Temperature data

The formation temperature model of the Berlín reservoir is only based on 31 PT (pressure temperature) logs from 40 geothermal wells (production and reinjection wells). This is because, in some reinjection wells, the total thermal recovery was affected by the urgency of injection during the first year of the field development.

According to the updated formation temperature in Berlín, three main zones have been identified for future development; the first one corresponds to the biphasic and saturated steam zone; the second one is the zone intercepted by; and the last one is the deep reservoir close to site drilled with the aim of increasing the production (LaGeo, 2007).

1.4 Current production status

In The Berlín Geothermal Plant there are three condensing units: two units of 28 MWe (Unit 1 and Unit 2) since 2000, one of 44 MWe (Unit 3) operating since 2007, and one binary unit of 9 MWe (Unit 4) since 2009. The system is connected to 40 wells, of which 16 are production wells, 20 are hot injection wells, and 4 are ambient injection wells (Monterrosa and Santos, 2013).

Over the past 29 years (1992-2021), the Berlín geothermal field has been in commercial operation through several stages of development. Currently, the installed capacity is 109.2 MWe, and the total mass extracted is around 890 kg/s (data registered in September 2021). The separated water is injected in three different ways: 1. A fraction of the separated water is injected at high temperatures (~ 172-180°C), transported directly from the separators to the reinjection wells; 2. water is injected at 140°C after transferring heat to the working fluid (isopentane) of the binary unit, and 3. water is injected at room temperature (60°C) by gravity or pumps (LaGeo, 2020a).

The total production is supported by two single flash, one double flash and one binary units. Figure 1 shows the wells and power plant location and the main fault system.

In the main production area, the extraction is higher than the reinjection, causing depressurization in the reservoir. Accordingly, a referable drilling targets are outside the area of principal production and reinjection (LaGeo, 2020b). Figure 3 shows the site proposal for drilling production wells, primarily to the east, west, and south of the current geothermal field. These areas are referred to in the last conceptual model report for the Berlín Geothermal field (LaGeo, 2019).

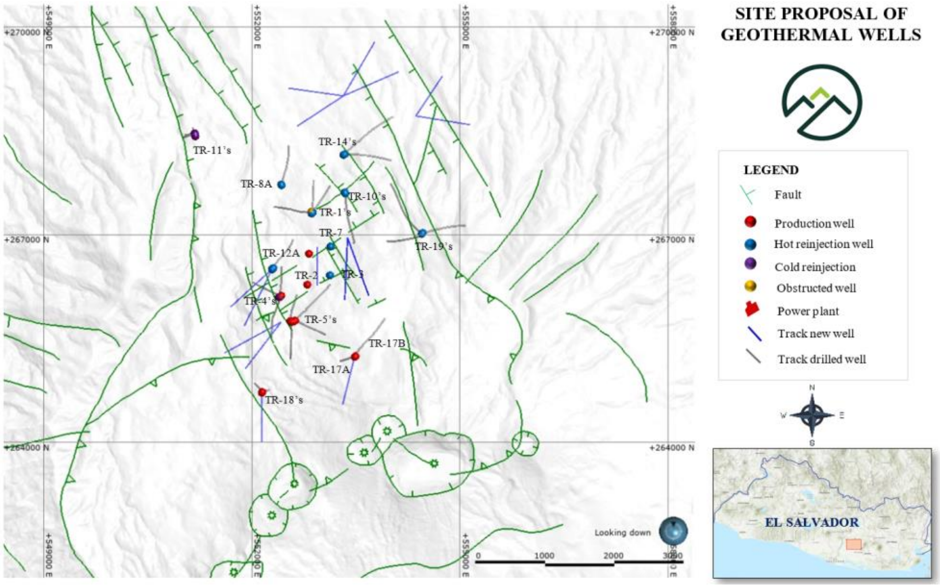

Figure 4: Proposed location of geothermal drilling in pink in Berlín Geothermal Field (modified from LaGeo, 2019). The inset map shows the location of the geothermal area in El Salvador.

2. A NEW WEIGHTED MODEL OF BERLIN GEOTHERMAL FIELD USING LEAPFROG GEOTHERMAL SOFTWARE

Leapfrog Geothermal with the Edge extension is the modeling program used in this project. According to the Leapfrog website (Leapfrog, 2021a), the software is a 3D implicit modeling tool and workflow tailored for geothermal experts, in their words "Leapfrog Geothermal is an intuitive, workflow-based 3D subsurface modeling software that enables you to build and refine models very quickly".

In this case, the software allows to build surfaces for different types of models with two different interpolants: the RBF interpolants if the data are from the wells, and Inverse Distance Weighted (IDW) grid interpolants for resistivity data. Each type of interpolants will be explained in the next sub-section.

After building the models with different interpolants, combined models, and some block models, the weighted model is created to quantify the most favorable drilling target in the area. ÍSOR was provided with an academic license of Leapfrog Geothermal with the "Edge" extension, which helps to check the estimates produced for blocks and inspecting the data used to create the estimated model.

The weighted model is created from calculations on the block model. Calculations use estimators and data to derive new values representing the quantification of favorable drilling targets in the area (Leapfrog, 2021b).

2.1 Methods and data

As briefly mentioned in the introduction to this work, a weighted model for the Berlín geothermal field is developed based on the last update of the conceptual model and other 3D models created in Leapfrog Geothermal, allowing an estimated quantification of the most promising drilling targets of the area. In addition, there are other technical reports with results from different geological, geochemical, and geophysical exploration studies. Some of the reports are only available for internal use; however, some results and data have been used for the weighted model. Following is the processing of development required to construct the weighted model.

First is important to start with the acquisition and preparation of the data to create the basis for the work that follows. Then, following the limits of the global data, the general boundaries of the model are determined. The area of the weighted model is 21 km^2.Subsection headings should be capitalized on the first letter.

2.1.1 Workflow

The surface data were imported as shapefiles and several maps of the area geo-referenced for some correlations between the data. Depths and thicknesses of lithological units, alteration minerals, temperature, and pressure were obtained from well logs. Finally, the data were organized in tabular format (including the seismic data) to be imported into the Leapfrog Geothermal database.

The workflow that was developed through the weighted model for the Berlín geothermal field is comprised of five main steps (Figure 5):

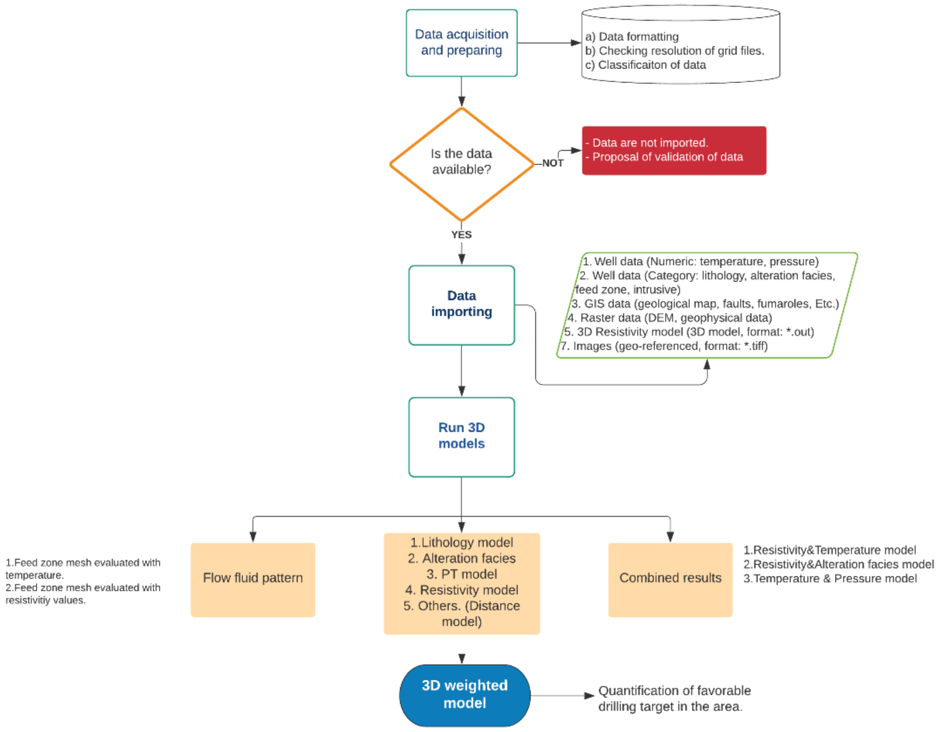

Figure 5: Workflow steps diagram utilized to create a 3D weighted model. This process could change with the acquisition of new data Proposed

2.1.2 Input data

Most of the data and information used in this work have been taken from a previous report (LaGeo, 2019) to create the 3D base models that are the input in the weighted model. The 3D models are new results in the three-dimensional view. They have allowed us to do new interpretations and correlations that support some of the hypotheses already put forward by LaGeo's experts and suggest some relevant aspects of the geothermal area.

Different types of data are used in this project. In constructing the 3D weighted model, it was necessary to apply manipulations to the information and data. Table 2 shows the four types of data imported into Leapfrog, especially using the Edge toolbox.

TABLE 1: Overview of different types of data imported into Leapfrog Geothermal.

Data	Explanation
Surface	Topography, surface geological map, GIS data (fault system, MT/TDEM sounding points).
Well	Lithology/hydrothermal alteration facies, location of feed zones, collar (wellhead location), and survey (well track, vertical and directional wells).
Well logging	PT logs of the last static logs in production and reinjection wells.
Others	3D resistivity model (based on MT data), location of seismic hypocenters.

2.2 Modelling results

The input data described in the sections above are presented differently with different 3D interpolants: RBF interpolants, IDW interpolants, maps, and cross-sections. Each result is the product of working with the data gathered in this project and the different ways to use it to build a new 3D model in Leapfrog Geothermal.

2.2.1 Lithology model

The lithology model shows four categories at different depth ranges (Figure 12). The proposed model represents a general interpretation of the movement of the rock blocks formed due to the activity of the central fault systems (NW-SE, NE-SW), the old Caldera of Berlín (north area), and Blanca Rosa caldera (south area).

The method used to generate the 3D lithology model uses the drill cuttings previously analyzed during the drilling period through thin slices for optical microscopy and macro/microscopic analysis of 27 cored wells in 2012. In 2020, the litho-stratigraphy was again evaluated to minimize errors in the lithology depths. This work applied a simple category as a big group of rocks identified in four lithological units: Unit I, Unit II, Unit III, and Unit IV.

Unit I is made up of superficial materials, Unit II contains pyroclastic rocks, Unit III is related to tuff, and Unit IV is made up of andesitic lava and corresponds to the geothermal reservoir. In the weighted model, the most favorable lithology unit corresponds to Unit IV, which has been assigned a priority level of 5.

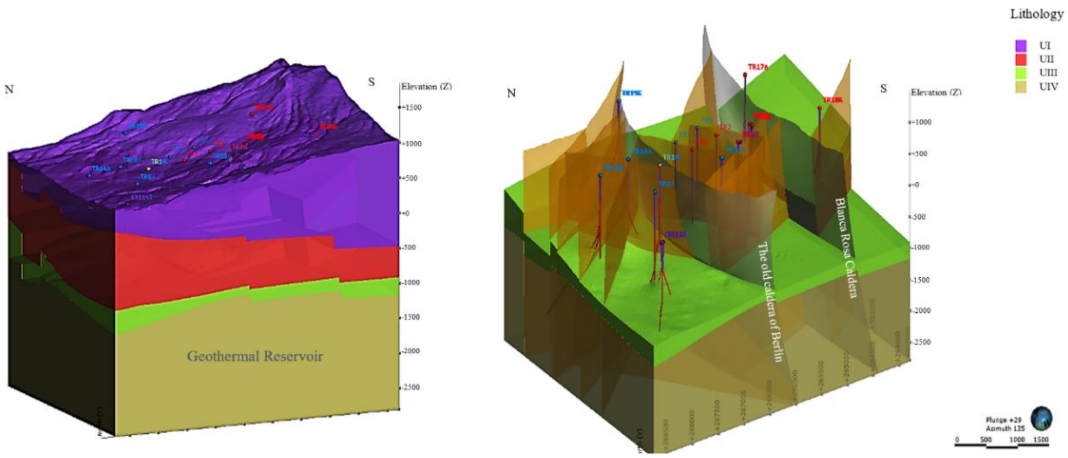

Figure 6: Lithological model of Berlín Geothermal Field and its interaction with the main fault system (normal/reverse faults and caldera boundaries)

2.2.2 Structural lineaments model

According to the lithological model discussed in section 3.4.1, the fault system could play an essential role in the fluid pattern. However, for simple effects and trying to understand the rocks' movement due to the faults, the model interacts only with the NW-SE and NE-SW systems and the two caldera boundaries (Figure 7).

The geological structure of the old caldera of Berlín was defined according to the Bouguer gravity anomaly (LaGeo, 2019). Blanca Rosa Caldera was inferred according to the significant difference between the lithological units in the center and south zones, which could be the geological barrier's effects.

Figure 7 shows both calderas collapse; however, in the south, another effect occurred. El Hoyón and San Juan faults in the south zone of the Blanca Rosa caldera collapse suggest reverse faults forming a geological structure named "Horst."

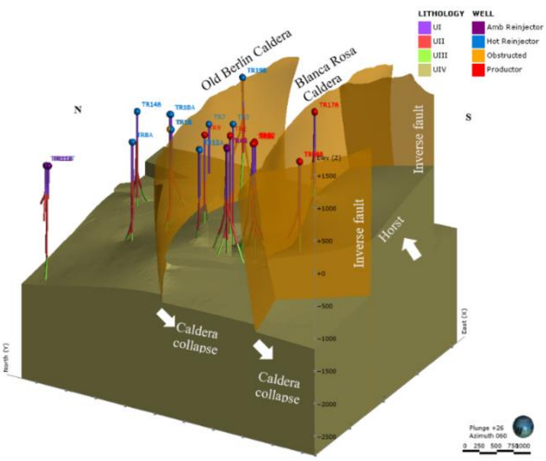

Figure 7: Structural model and type of geological structures in the Berlin geothermal area. The figure legend shows the lithology units from wells and the type of geothermal well

2.2.3 Hydrothermal alteration facies model

The hydrothermal alteration facies were used to build the 3D alteration facies model. The propylitic and potassic facies contain high-temperature alteration minerals; thus, it is essential to interpret their distribution in the reservoir area.

The model is calibrated using the resistivity values corresponding to the low resistivity cap (<15 Ωm). The purpose is to delimit the bottom part of the smectite layer (argillic-phyllic facies) and obtain a more consistent interpretation of the area. In this study, the fault system has not been included in the model.

Figure 8 shows the hydrothermal alteration facies model. The layers follow the behavior and thickness information from the geothermal wells, making the model acceptable. However, in areas where there is no information from wells, the iso-surfaces of the facies have been calibrated with respect to the resistivity values corresponding to the base of the conductive layer (8-15 Ωm), the top of the layer transition (15-22 Ωm) and the top of the reservoir (30-34 Ωm) for the phyllic, phyllic-propypillic, and propypillic facies, respectively.

Another aspect of the model is that the potassic facie related to the formation of high-temperature minerals (> 250°C) seems to have the shape of a semi-circular contour in the vicinity of well TR-19. Therefore, the proposed interpretation would be the relationship of this high-temperature facie to a possible high-temperature source and its relationship with an intrusion model. However, as deeper wells are drilled in the area, the limits of this layer could be better adjusted.

The layers with a high favorability level in the weighted model are Phyllic-Propylitic alteration facies, which correspond to temperatures >250°C.

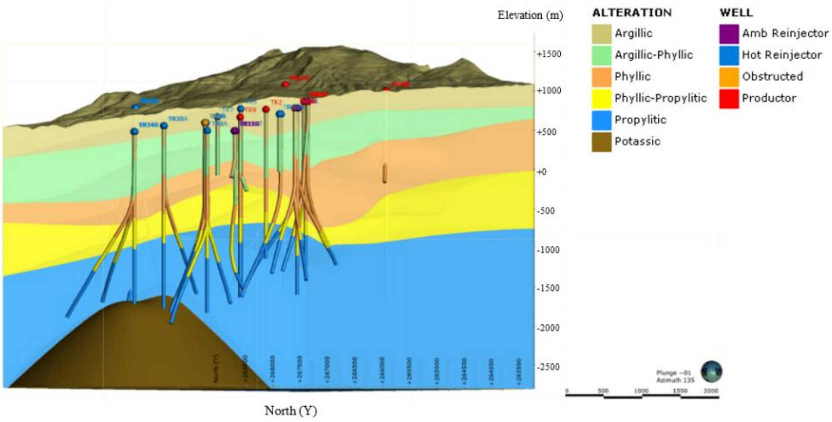

Figure 8: Hydrothermal alteration facies model. **The figure legend shows the hydrothermal alteration facies from the wells.**

2.2.4 Resistivity model

The 3D resistivity model was built using the IDW interpolation model in Leapfrog Geothermal. The format of the original imported file is *.out, and later it was delimited to similar dimensions of the lithological model.

The purpose of generating the electrical resistivity model of the Leapfrog Geothermal is to correlate it with different models for the calibration of the facies model and to use it in the weighted model. Therefore, in this section, the model has not been modified with any artifice; however, cross-sections and some views were created to verify the results obtained using IDW (Inverse Distance Weighted) grid interpolants.

The IDW is a unique way to work with the resistivity data in Leapfrog Geothermal. This interpolant helps to generate iso-surfaces and volumes from large datasets, such as regular or semi-regular grids, interpolating points as an average of up to eight nearby samples, weighted by their distance (Leapfrog, 2021b).

Figure 9 shows a cross-section in the E-W direction with the electrical resistivity values obtained from the 3D model. The figure shows a correlation between the resistivity corresponding to altered granite and the hydrothermal alteration facies at great depth (see section 2.2.3).

The 160 Ωm iso-surface (blue line) represents the top of the granite (red line) in the northern zone (intercepted by wells TR-14B, TR-19A, TR-19B, and TR-19C) and potassic alteration facie (white line) (see Figure 9). The above supports the hypothesis that the area where the granite and high-temperature alteration minerals are found possibly corresponded to a heat zone. The rock alteration is due to the high temperatures and geothermal fluids, as indicated by the resistivity values. The model suggests that the rock has probably been cooled over time due to inconsistency between the values of an intrusive rock without alteration.

The range of resistivity values with a high level of favorability corresponds to the top of the reservoir with resistivity values between 30-45 Ωm and its base with values between 45-90 Ωm.

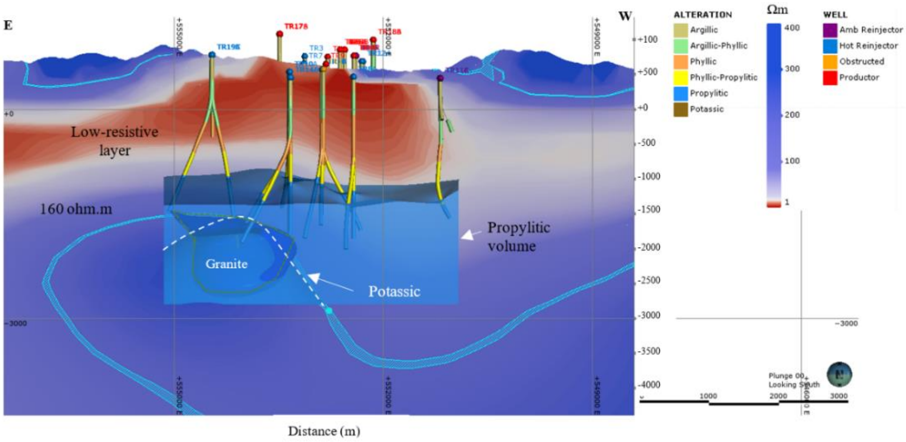

Figure 9: Correlation between resistivity, hydrothermal alteration facies, and granite model

2.2.5 Temperature model

The stabilized temperature profiles obtained from the last PT profile in each well were used to build the 3D RBF model that indicates the areas where the temperature is significantly high. Figure 10 shows a cross-section from north to south with the production and reinjection wells located near the section.

The temperature model indicates a high-temperature iso-surface that is confined between two main structures (caldera boundaries), which suggests being the main up-flow in the center of the geothermal field, exactly where the good production wells are. In the weighted model, the best parameters that indicate a good productor reservoir corresponds to temperatures > 2900ºC.

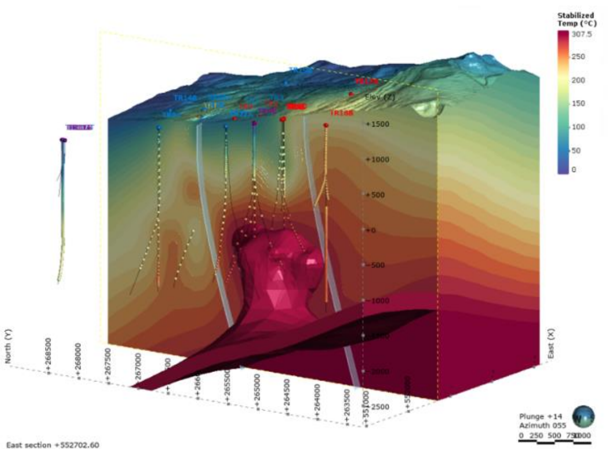

Figure 10: 3D temperature model using stabilized temperature profile of geothermal wells

2.3 The weighted model

Integrating multiple data sets enables advanced processing and calculations like Play Fairway Analysis (PFA), a methodology adapted from the oil industry that integrates data at the regional or basin scale to systematically define favorable plays for exploration (Shervais et al., 2020). In this work, the favorable model corresponds to a weighted model where the weight value for each model is defined according to parameters or characteristics that better describe the geothermal reservoir. After the characterization of the reservoir, it proceeds to calculations to obtain the favorable areas that represent the best drilling target. Figure 11 shows the weight values applied to the models included in the weighted model.

The block model size of the evaluations and calculations used has dimensions of 50 m for the X, Y, and Z axes. After creating the block model, the next step is to identify the priority levels for each model evaluated and discussed in the previous sections. The priority levels range from 0 to 6. The value five and six are the most relevant in the weighted model, representing the characteristics of the area of the potential geothermal reservoir (see Table 2).

TABLE 2: Priority levels for the categories related to the reservoir in each model

Model	Category	Priority level
Lithology Units (L)	Unit IV	5
Hydrothermal alteration facies (HF)	Phyllic-Propylitic	4
	Propylitic	5
Temperature (Tst)	>250ºC	5
Electrical Resistivity (R)	10-30 Ωm	4
	30-90 Ωm	5
Distance function to the fault system (Df)	0-100 m	5
	100-150 m	4
Distance function to hypocenter (Dh)	0-50 m	5
	50-100 m	4
Distance function to feed zones (Dfz)	300-400 m	5
	>400 m	6
Distance function to drilled wells (Dw)	300-500 m	4
	>500 m	5

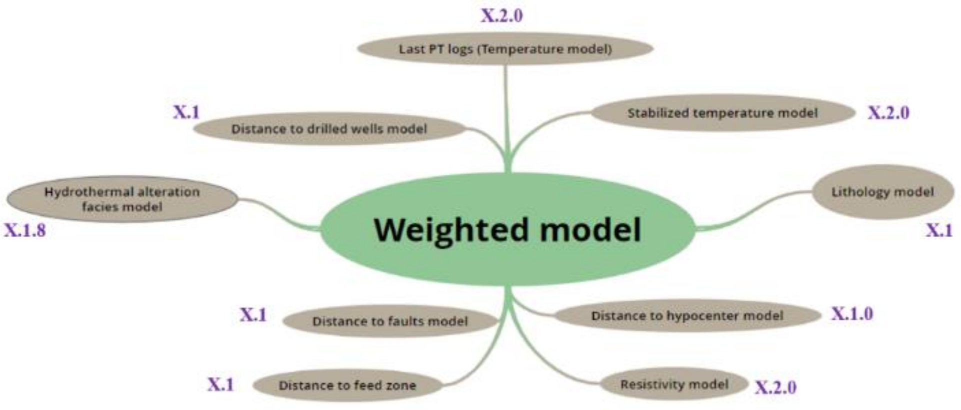

Figure 11: Weight values applied to the models included in the weighted model

Equations from (2) to (9) show the levels applied for each model. Figure 11 shows the schematic flow of how the weighted model was built and the weight values for each model. Equations (10) to (14) show the different evaluations and weights for each model, starting from a simple model (Equation 10) to a more complex one (Equation 14).

$$Wm_1 = [(1.0 * L) + (1.8 * HF) + (2.0 * Tst) + (2.0 * R)]/3.5 \tag{10}$$

$$Wm_2 = \ (1.0 * L) \ + (1.8 * HF) \ + (2.0 * Tst) + (1.5 * Dh) + (2.0 * R))/4.15 \tag{11}$$

$$Wm_3 = [(1.0 * L) \ + (1.8 * HF) \ + (2 * Tst) + (1.5 * Dh) + \ (2.0 * R) + (1.0 * Df)]/4.55 \tag{12}$$

$$Wm_4 = [(1.0 * L) \ + (1.8 * HF) \ + (2 * Tst) + (1.0 * Dh) + \ (2 * R) + (1.0 * Dfz) + (1.0 * Dw)]/4.85 \tag{13}$$

$$Wm_5 = [(1.0 * L) \ + (1.8 * HF) \ + (2 * Tst) + (1.0 * Dh) + \ (2 * R) + (1.0 * Df) + (1.0 * Dfz) + (1.0 * Dw)]/5.4 \tag{14}$$

For better visualization of the new weighted model for the Berlín geothermal system, Figure 12 shows a map view in which different areas of interest have been represented according to the high level of favorability between 8.0 to 10.0 to be considered as drilling target areas for new production wells. Figure 13 show two groups of favorability areas between 8.5 to 10.0 for the Wm_5: the first group (1, 2, 3, 4, and 5) corresponds to the primary zones represented in a green square where the extrapolation is less than other model areas, and areas 6, 7, and 8, corresponding to the secondary areas that aim to explore new production wells represented in a blue square. The secondary area has high uncertainty because it represents the extrapolation in the model. However, this could be calibrated with results from new wells.

Another important aspect of the weighted model is observed in the reinjection wells TR-12, TR-3, and TR-7, where there are also favorable areas for drilling new producing wells. However, the location of the reinjection wells has not been considered in the model; however, it is interesting to note that there are good probabilities of finding a favorable geothermal resource in the study area but at greater depths. The reinjection wells drilled in this area do not reach depths greater than 2,400 m; therefore, they do not intercept the model.

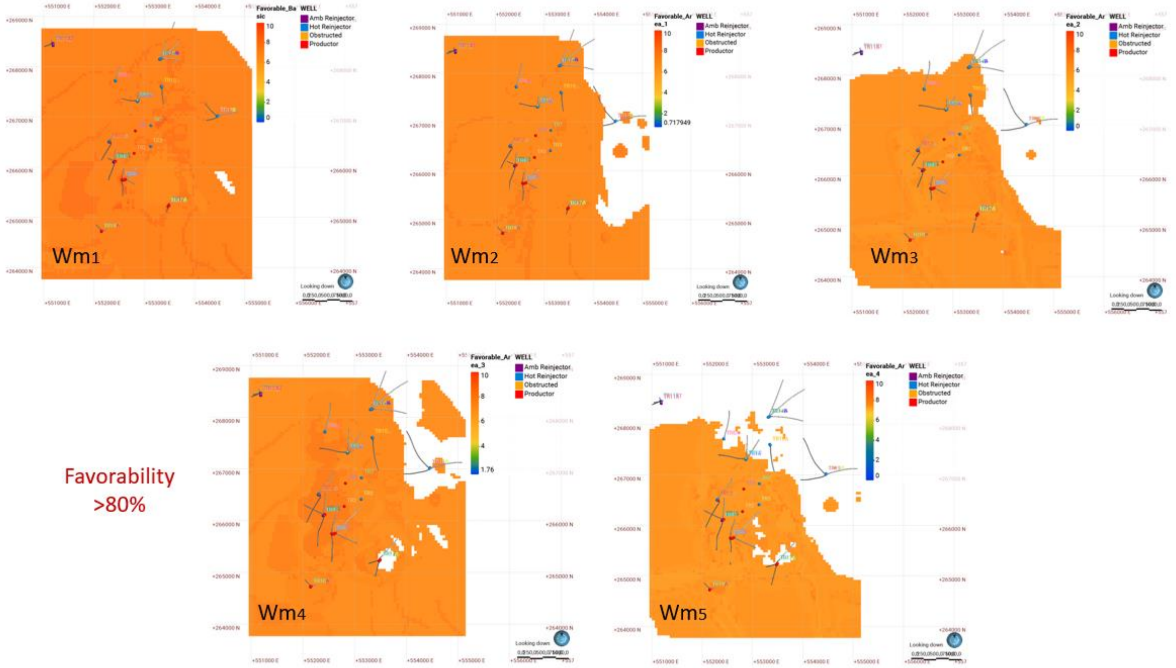

Figure 12: 3D weighted model 1, 2, 3, 4, and 5. The maps show the favorability areas> 80%, where model 1 indicates a simple and basic model and model 5 a more complex and high accuracy of the convergency of the best parameter that represent the best areas to drill new production wells.

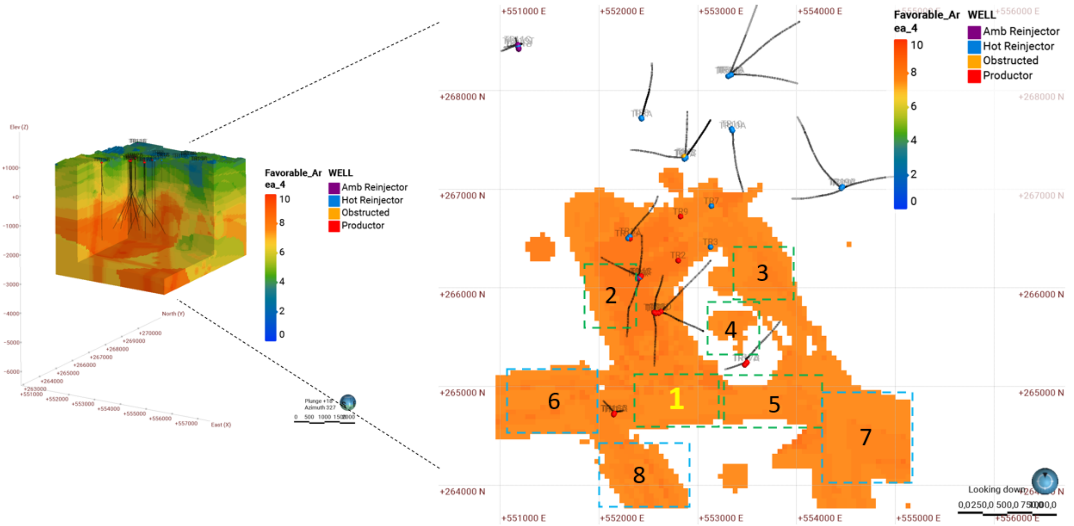

Figure 13: 3D weighted model of the Berlìn Geothermal field. The figure shows the most favorable area to drill new production wells (green square) and the secondary favorable areas (blue square).

2.3.1 Discussion

For the first part of this study, all geoscientific data were gathered, digitized, and standardized in terms of units and formats. The available data were used to revisit the conceptual model to construct a three-dimensional (3D) model of each type of data or information and construct a weighted model that indicates the most favorable drilling target in a range of values from 0 to 10 (see the color scale in the weighted models); however, the results in this project are delimited from 8 to 10 because represent the volumes where the most important parameters of each model are high and converge. The 3D models were created in the Leapfrog Geothermal 3D modelling tool; however, chemical data and alteration minerals from wells have not been included in the weighted model due to limited time to order the information in the format required in the software.

The 3D lithology model was built using information from the core of wells (information validated and analyzed by geologists from LaGeo, LaGeo, 2019). The model interacts with the main fault systems of the area (NW-SE and NE-SW system and the two caldera boundaries). The model suggests block motions created according to the fault type (normal or reverse); therefore, they were analyzed according to the depth of the four rocks units (I, II, III, and IV). The movements of the rock blocks proved to be consistent according to the lithology information and the intersection with some feed zones. Therefore, the model suggests that some faults, primarily the Calderas boundaries, have affected the rock deposits and that the caldera structure plays an important role in the fluid flow and its connection with the fluid patterns in this area. This is consistent with the injectivity index between the production and reinjection wells. The earlier data presentation included dip and azimuth values inferred for the faults. However, that does not affect the distribution of the rock deposits because the values have not been exaggerated. Now, the lithological 3D model is in digital form, which can benefit future modeling work in the area.

The 3D hydrothermal alteration facies were modelled to show the trend of the alteration facies and the high-temperature environment (based on the temperature required for mineral formation). The model was calibrated by the resistivity data and compared with the current and stabilized temperatures. The results show a seal layer (argillic-phyllic facie) beginning at 860 m b.s.l. in the southern part indicating a stabilized temperature range 178-235°C. The temperature in the neighbouring wells TR-17 and TR-18 is currently around 185-247°C, indicating an increase of temperature in the southern area. However, a decrease in temperature has been identified in the northern zone, specifically in wells TR-8, TR-14, and TR-19, observing a decrease of ~ 30°C in the first two platforms and ~ 19°C in the TR-19 platform. With this hydrothermal alteration facies, a detailed data of alteration minerals could be added to the model to generate a more confident model of the lithology to be related to different temperature models.

A 3D feed zone model was constructed using the main feed zone of each geothermal well to infer the trend of geothermal fluids in the area. In addition, the model was evaluated from the temperature and pressure data to correlate with different parameters that suggest a better characterization of the model. The mesh covers all geothermal wells (production and reinjection wells), and it is observed between 500 m and 1,100 m depth that the superficial fluids are limited in the northern part by the old Berlín Caldera This implies that the fluids are possibly reaching to greater depth to the north. The current pressure evaluated in the mesh is around 33 bar g in well TR-18 where the steam cap has been identified, and similar values are found in the well TR-17. However, in the wells located in the central and north areas, the pressure increases, and the temperature decreases, possibly by reinjection. The high-temperature values have been identified close to the wells TR-5 and TR-4, which support the possible up-flow zone in the central area. In addition, the evaluation of the resistivity model indicates that the southern and central zones intersect part of the seal cap (6-10 Ωm) of the system.

The correlation between the resistivity and temperature models has demonstrated that it is possible to build relationships representing the geothermal reservoir. Therefore, its possible extension can be characterized according to specific ranges of resistivity and temperature. The resistivity values used were from 30 to 50 Ωm, and temperatures values >260°C, correlated with some structural faults of the system, which suggest being the primary limits for the top of the reservoir. The model could represent a good input in updating the possible producer resource as new information is obtained from well PT profiles or the update of the resistivity model.

Finally, the correlation in the weighted model through the different 3D models indicated in this study presents a good visualization and representation of the geothermal system. The use of Edge extension in Leapfrog Geothermal has permitted modeling of the most favorable drilling target areas and quantification in a range from 1-10 (or 10-100%). From the five weighted models, model number 5 is the best because it considers as many models and data as possible to decrease the uncertainty. There are five favorability areas with values >85%, and the second favorability areas are 3 with >85% of success; however, due to the extrapolation in the model, the uncertainty could be significant in the second area. However, the weighted model could represent an excellent input and tool to explore new drilling target areas. In addition, the update and calibration with new well(s) drilled or more detailed information could help improve the weighted model.

2.3.2 Conclusion and recommendations

The Berlín Geothermal field has been utilized since 1992 when the first two back pressure units were installed as a pilot project. As the area was explored and utilized over the past 29 years (1992-2021), a significant number of reports have been published including six updated reports for the conceptual model of The Berlín geothermal field. This has made it possible to identify and propose new drilling targets for production and reinjection wells.

One of the main objectives of this project was to generate and suggest a workflow approach for the construction of the different types of models of the geothermal area that are the main inputs for the weighted model. Throughout the modelling process for the Berlín geothermal field, data comparison, combining, and evaluation of various data sets revealed and confirmed different aspects of the latest conceptual model. However, it also revealed new aspects that help understand and characterize the geothermal reservoir in another way, resulting in a new input to discuss some problems in the reinjection and production areas influenced by the fluid patterns and the structural system. Thus, evaluating new drilling targets for production wells has been proposed through all models in the weighted model.

The previous data have been interpreted and updated to a digital format to be integrated into a 3D model. The main 3D models are presented in this project, their correlation and integration in the weighted model. Additionally, the modelling approach and methods are briefly discussed.

An advantage of the evaluation in the weighted model is the dynamic update with new acquisition data. In addition, the results provide a lower risk of drilling.

- Update and calibrate the weighted model according to the new data obtained and additional information from the new producing wells and injectors in the favorable areas.

- Include detailed information on the deep geochemistry of the geothermal wells in the weighted model.

- Include the seismic tomography model in the weighted model to support the possible heat source and ascent zones of geothermal fluids.

- Design the technical profile of the new wells to be drilled, considering as priority areas for drilling objectives, the areas with the least extrapolation of the weighted model 5, that is, in areas 1, 2, 3, 4 and 5. In addition, areas 6, 7 and 8 would be considered as new exploratory zones.

REFERENCES

Asunción, A. and Pabón, M.: Methodological proposal for the social acceptance of geothermal projects of direct use in communities within zones of geothermal interest in El Salvador (in Spanish). *Geothermal Training for Latin America 2019*. Universidad de El Salvador, San Salvador, El Salvador (2019).

Browne, P.R.L.: Hydrothermal alteration in active geothermal fields. *Annual Reviews of Earth and Planetary Science*, 6, 229-250. New Zealand (1978).

Franzson, H.: Chemical transport in geothermal systems in Iceland: Evidence from hydrothermal alteration. *Journal of Volcanology and Geothermal Research*, 173, 217-229 pp. Iceland (2008).

DeMets, C.: A new estimate for present-day Cocos-Caribbean plate motion: Implications for slip along the Central American volcanic arc. *Geophysical Research Letters 28*(21): 4043-4046. DOI:10.1029/2001GL013518. (2001).

Giao, P.H., Weller, A., Hien, D.H. and Adisornsupawat, K.: An Approach to construct the weathering profile in a hilly granitic terrain based on electrical imaging. *Journal of Applied Geophysics 65*(1): 30-38. (2008).

Hersir, G.P., Gudnason, E.Á. and Flóvenz, Ó.G.: Geophysical exploration techniques. In: Letcher, T., (ed.) *Comprehensive Renewable Energy – 2nd edition, Vol 7*. Available at: *https://doi.org/10.1016/B978-0-12-819727-1.00128-X*. Elsevier, Oxford, United States. (2021).

Shervais, J.W., Glen, J.M., Siler, D., Liberty, L.M., Nielson, D., Garg, S., Dobson, P., Gasperikova, E., Sonnenthal, E., Newell, D., Evans, J., DeAngelo, J., Peacock, J., Earney, T., Schermerhorn, W. and Neupane, G.: Play Fairway analysis in geothermal exploration: The snake river plain volcanic province. SGP-TR-216. *Proceedings,* 45th Workshop on Geothermal Reservoir Engineering Stanford University, Stanford, California (2020).

Kristmannsdóttir, H.: Alteration of basaltic rocks by hydrothermal activity at 100-300°C. In: Mortland, M.M., and Farmer, V.C. (editors), *International Clay Conference,* (1978), 359-367. Elsevier Scientific Publishing Co., Amsterdam.

Kristmannsdóttir, H.: The role of clay minerals in geothermal energy research. *Uppsala Symposium Clay Minerals-Modern Society,* (1985), 125-132. Uppsala, Sweden.

LaGeo: Synthesis of potential of new geothermal areas. *Internal source (in Spanish),* Santa Tecla, El Salvador (2021).

LaGeo: Maximum steam flow rate in the productor wells, period 2020-2021 *Internal source (in Spanish),* Santa Tecla, El Salvador (2021).

LaGeo: Annual Operation Report, Berlín Geothermal Power Plant, 2020. *Internal source (in Spanish)*, Santa Tecla, El Salvador (2020).

LaGeo: Sustainability and development of the Berlín geothermal field. *Internal source (in Spanish)*, Santa Tecla, El Salvador (2020).

LaGeo: Conceptual model of the Berlín geothermal field, 2019. *Internal source (in Spanish)*, Santa Tecla, El Salvador (2019).

LaGeo: Tracer Test Report conducted in 2018 in TR-12A and TR-4A reinjection wells - Berlín Geothermal Field. *Internal source (in Spanish)*, Santa Tecla, El Salvador (2018).

LaGeo: LaGeo sustainability Protocol report. *Unpublished report (in spanish)*, Santa Tecla, El Salvador (2011).

LaGeo: Reservoir engineering update in The Berlín Geothermal Field. *Internal source (in Spanish)*, Santa Tecla, El Salvador (2007).

LaGeo-SIGET (Superintendencia General de Electricidad y Telecomunicaciones), 2012: Berlín Geothermal field sustainability protocol: Calculation of the sustainable energy value Eo, 13pp, *Internal source (in Spanish)*, Santa Tecla, El Salvador (2012).

Leapfrog: What is implicit modelling? Seequent (Aranz Geo Limited), webpage: https://www.seequent.com/products-solutions/leapfrog-geothermal/. [Accessed 18 October 2021]. (2021).

Leapfrog: Inverse Distance Weighted Grid Interpolants. Seequent (Aranz Geo Limited). Available at: https://help.seequent.com/Geothermal/4.1/en-GB/Content/interpolants/idw-interpolant.htm (2021).

Montalvo, F. and Axelsson. G.: Assessment of chemical and physical reservoir parameters during six years of production-reinjection at Berlín Geothermal field (El Salvador*). Proceedings of the World Geothermal Congress 2000,* 2153-2158, Ksushu-Tohoku, Japan (2000).

Monterrosa, M. and Santos, P.: Conceptual models for the Berlín Geothermal field, case history. *Presented at Short Course V on Conceptual Modelling of Geothermal systems,* organized by UNU-GTP and LaGeo, 9 pp, Santa Tecla, El Salvador (2013).

Reyes, A.G.: Petrology and minerals alteration in hydrothermal systems: from diagenesis to volcanic catastrophes. *Report 18 in: Geothermal Training in Iceland 2000*. UNU-GTP, 77 pp, Iceland (2000).

Rodriguez, V.A., 2005: Analysis of temperature and pressure measurements and production data for Berlín Geothermal field, El Salvador. *Report 16 in: Geothermal Training in Iceland 2005*. UNU-GTP, 36 pp, Iceland (2005).

Wilson, S.H., 1960: Physical and chemical investigation of Ketetahi Hot Springs. In: The Geology of Tongariro Subdivision, D.R. Gregg. *NZ Geological Survey Bulletin 40*, 124-144 pp, Wellington, New Zealand (1960).